# MICROGRIDS

# Systemic Economic-Environmental Analysis for Building-Scale Microgrids

by


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# Outline

## DER-CAM OVERVIEW

- introduction to the Distributed Energy Resources ) Customer Adoption Model (DER-CAM)
- three types of analysis application (commercialization):
  (single building/microgrid, policy, real-time control)
- results (new and old)
  (CERTS Microgrid biz case, ZNEB, EV charging, valuing PQR)

## MICROGRIDS

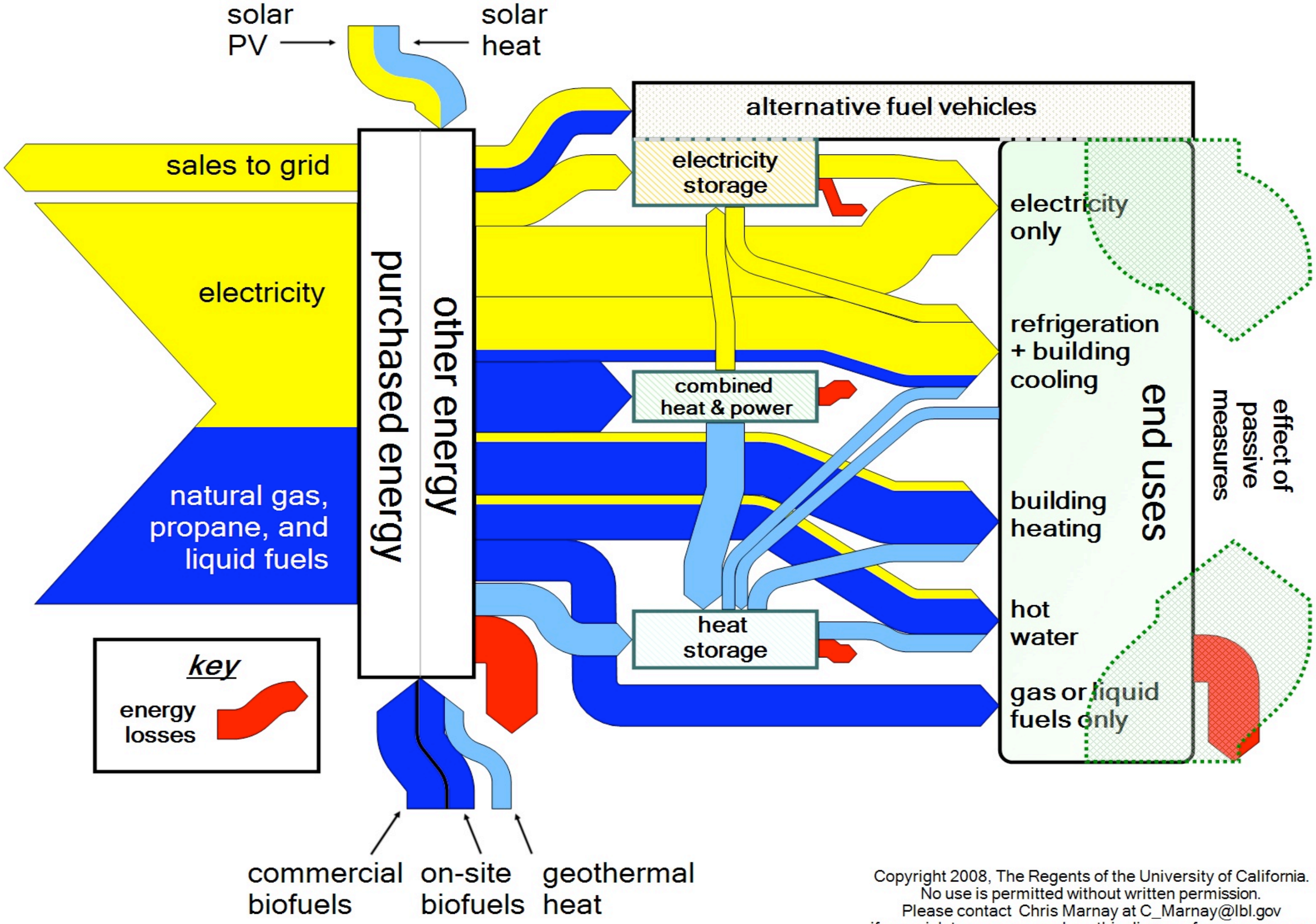
- definition, example, and philosophy

## MISCELLANEA

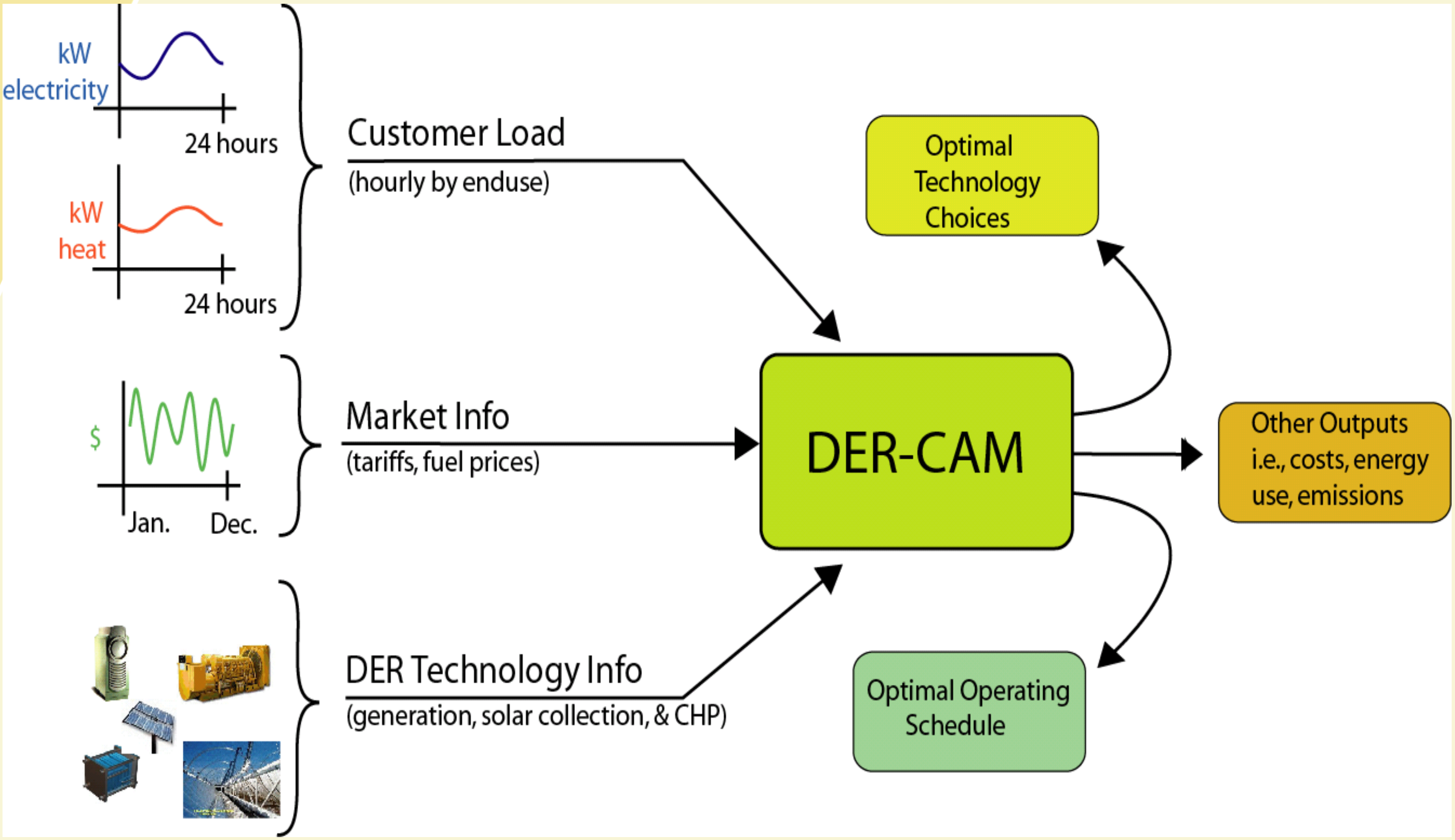
- DER-CAM math & specifying equipment options
- demand-side/energy efficiency measures
- zero net energy buildings
- valuing power quality and reliability

# DER-CAM Overview

# DER-CAM Concept



# DER-CAM Logic



# CA Nursing Home Results

(cost min. cases with eff./beh., ZNEB, and subsidies)

| RUNS | 1: do nothing | 2: all techs +eff | 3: all techs +subs | 4:all techs+eff +ZNEB | 5: same as 4 +subs |
|---|---|---|---|---|---|
| 100 kW recip. engine w/HX (kW) | n/a | 300 | 300 | 0 | 200 |
| abs. chiller (kW.e displaced) | | 0 | 40 | 238 | 0 |
| solar thermal (kW.t) | | 0 | 43 | 3952 | 0 |
| PV (kW) | | 0 | 517 | 2408 | 3162 |
| electric storage (kWh) | | 0 | 2082 | 0 | 1514 |
| thermal storage (kWh) | | 0 | 47 | 9897 | 0 |
| annual costs (k$) and percentage savings | | | | | |
| total (incl. annualized equip. cost) | 964 | 721 | 910 | 1783 | 829 |
| savings cmprd. to do-nothing (%) | n/a | 25 | 6 | -85 | 14 |
| annual utility energy consumption (GWh) | | | | | |
| electricity | 5.8 | 2.1 | 2.4 | 3.4 | 2.3 |
| NG | 5.7 | 8.9 | 10 | 0.004 | 7.5 |
| energy sales (GWh) | | | | | |
| electricity | n/a | n/a | n/a | 3.4 | 4.9 |
| annual $CO_2$ emissions (t/a), *does not contain $CO_2$ offset due to electr. sales* | | | | | |
| emissions | 3989 | 2704 | 3058 | 1752 | 2548 |
| savings cmprd. to do-nothing (%) | n/a | 32.2 | 23 | 56 | 36 |

CHP appears in solution

ZNE reached at a cost increase of approx. 85%

utilizing a *subsidy* for PV and storage of M$13, or a $CO_2$ emission reduction cost of $259 /t$CO_2$ compared to a $18/t$CO_2$ market price

- run 1 do nothing (buy gas & electricity at standard tariffs)
- run 2 all techs. considered + efficiency/behavior
- run 3 all techs. considered + subsidies for PV (60%) & storage (70%)
- run 4 all techs.. considered + efficiency/behavior + ZNEB constraint
- run 5 all techno. considered + efficiency/behavior + ZNEB constraint + subsidies

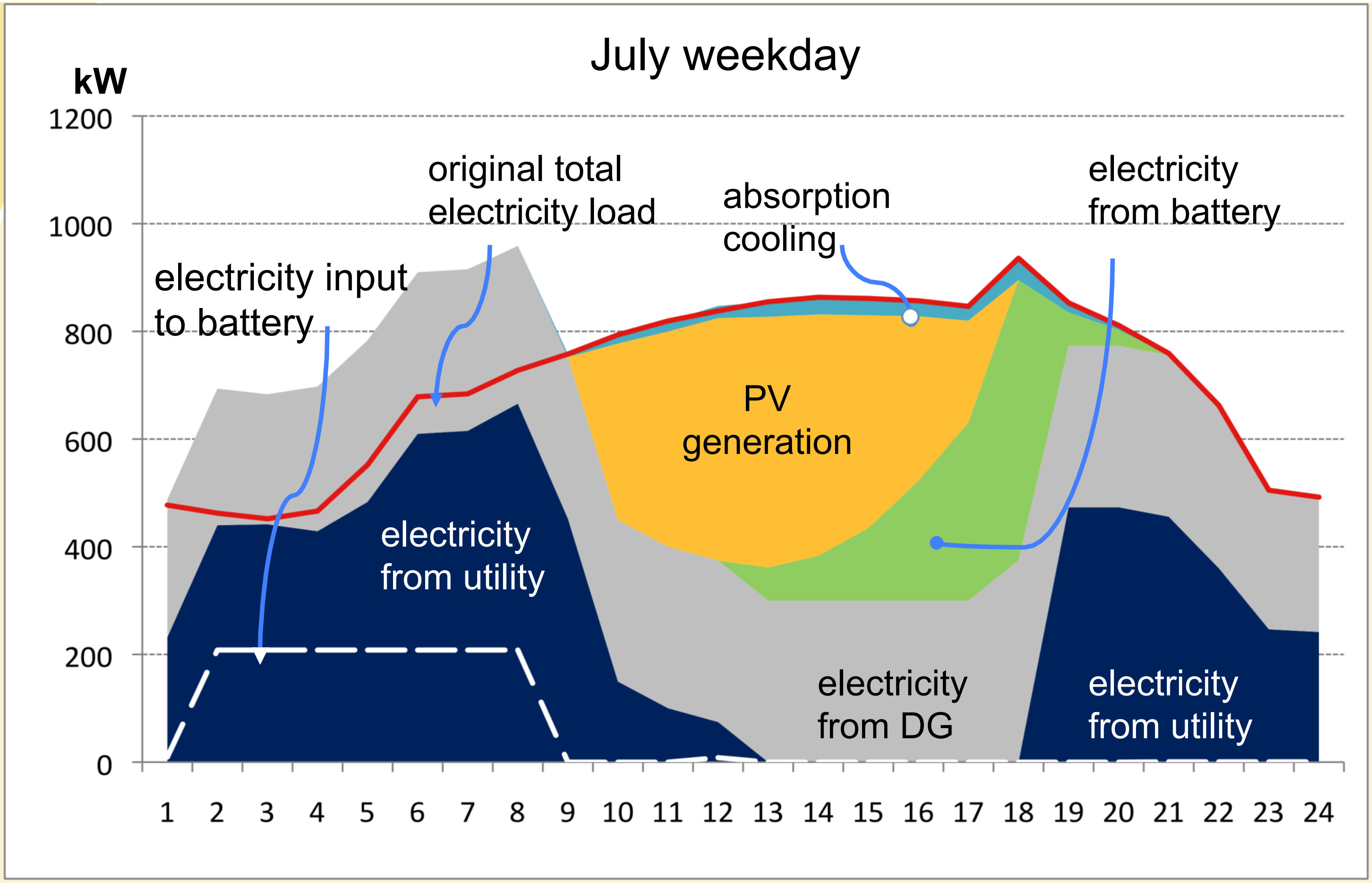
***subsidies:***
***PV = $4005/kW***
***E. storage = $133/kWh***
***T. storage = $50/kWh***



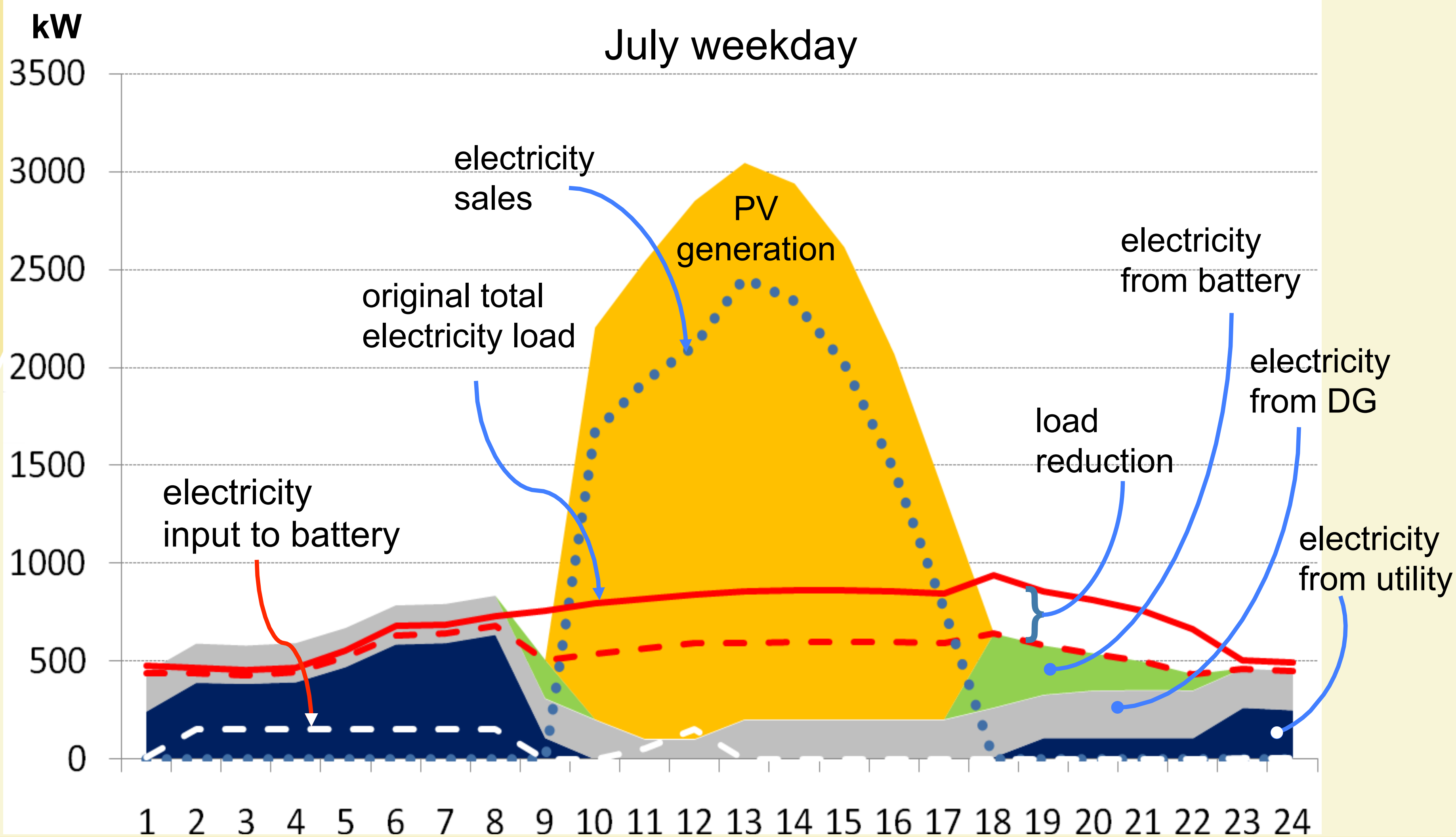
* constant grid marginal CO2 emission rate = 513 g/kWh

# Electricity Balance at N.H.

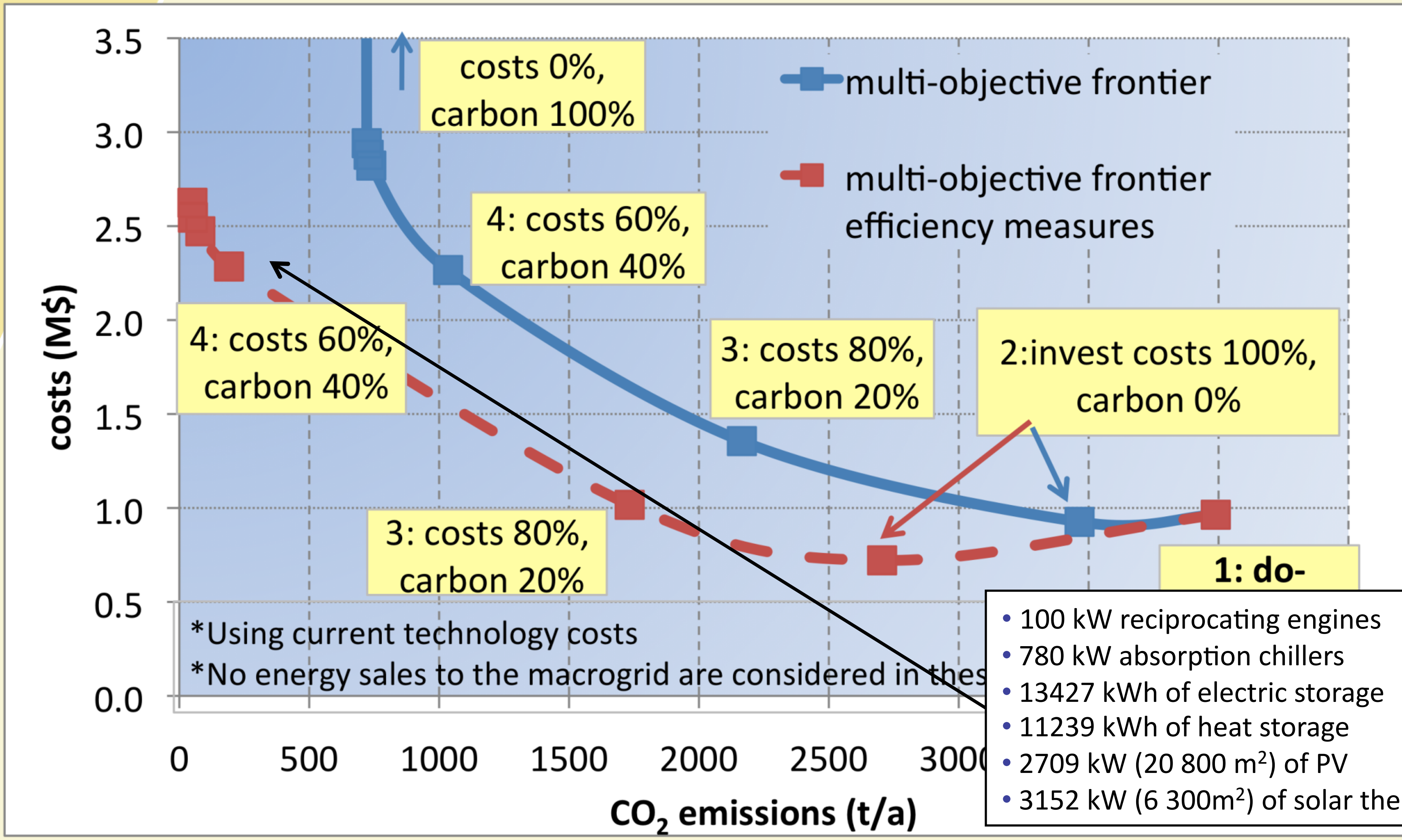
(run 3: PV and storage subsidies)



# Electricity Balance at N.H.
## (run 5: eff. + ZNE + PV/storage subs.)

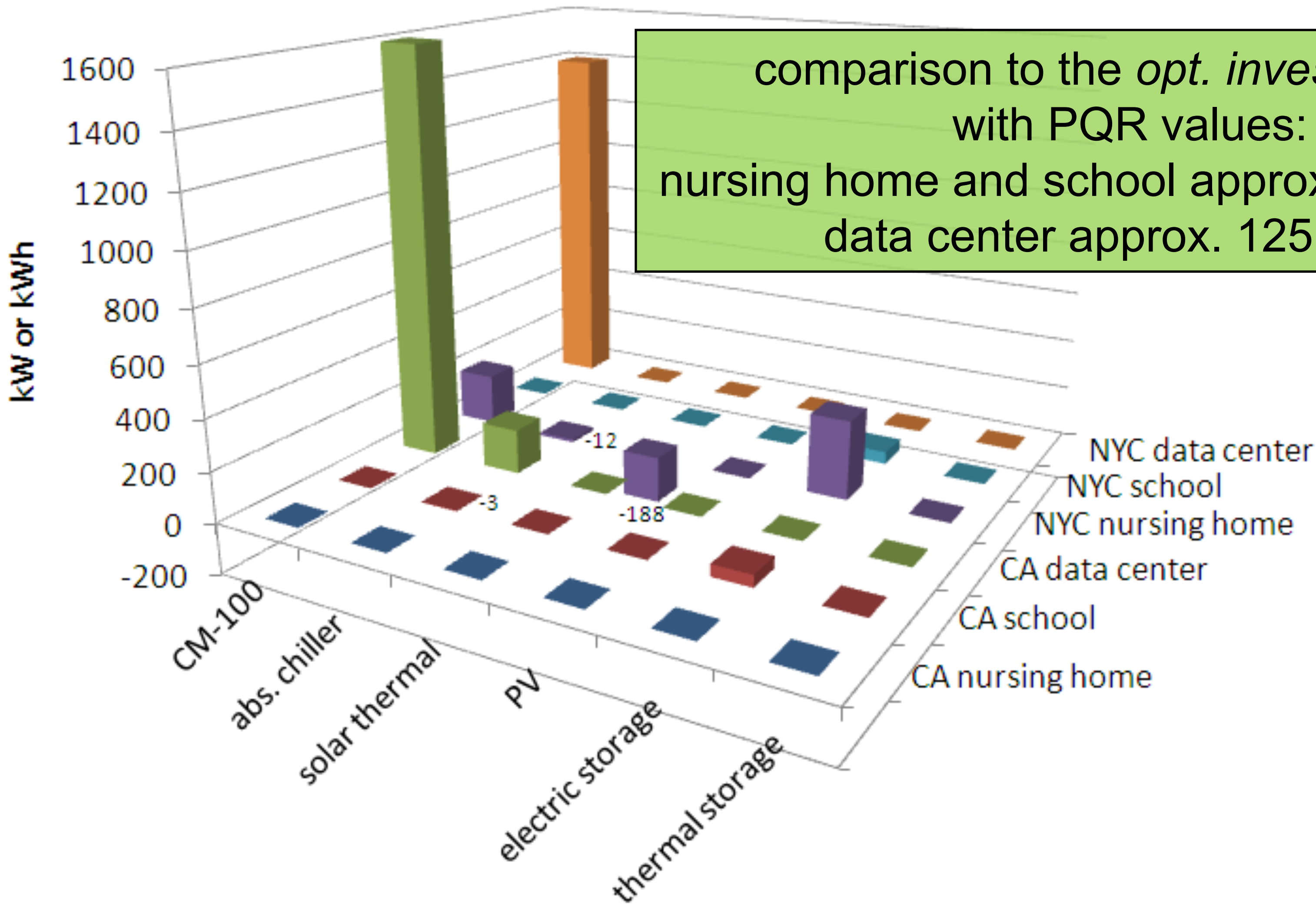


# Cost-Carbon Frontier
## (no ZNE constraint)




- 100 kW reciprocating engines
- 780 kW absorption chillers
- 13427 kWh of electric storage
- 11239 kWh of heat storage
- 2709 kW (20 800 m²) of PV
- 3152 kW (6 300m²) of solar thermal

# Added PQR Results




comparison to the *opt. invest.* cases,
with PQR values:
nursing home and school approx. 25 $/kW•a,
data center approx. 125 kW•a

# EVs and Microgrids

- electric vehicle interactions with buildings quite unexplored
- DER-CAM a useful tool to understand how EVs might optimally be used by microgrids
- to explore how would EVs be used and what their value is
- developed capability to optimally operate electrical storage
- EV interactions cannot be considered in isolation
- representation of constraints very complex (battery degradation, driving behavior, contracts, …)
- confused legal and economic institutions
- currently exploring two types of EV effects:
  - employee vehicles parked for work day at buildings
  - value of used EV batteries as stationary storage

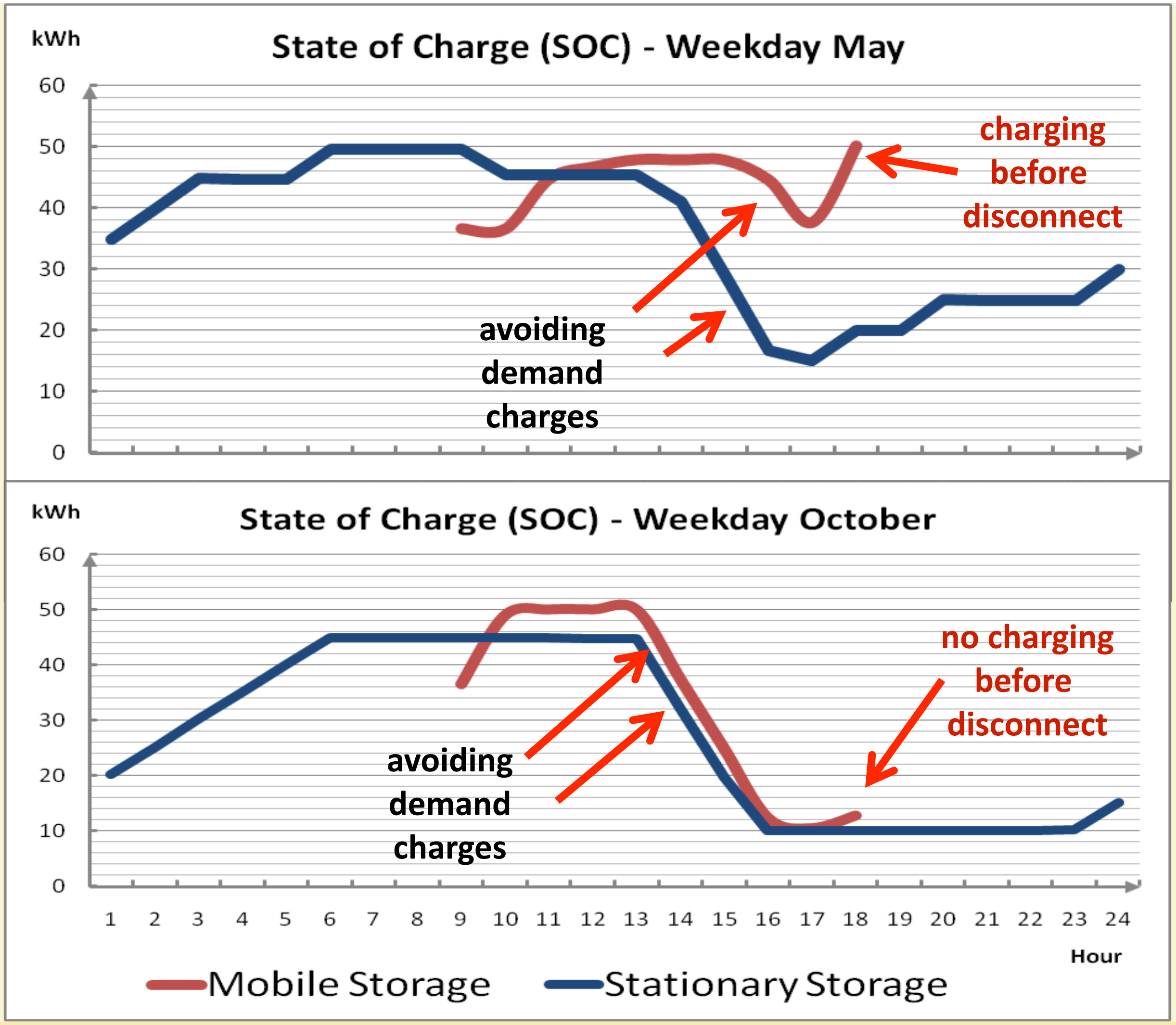
# Preliminary Results

## (batteries and EVs at small S.F. office blg.)

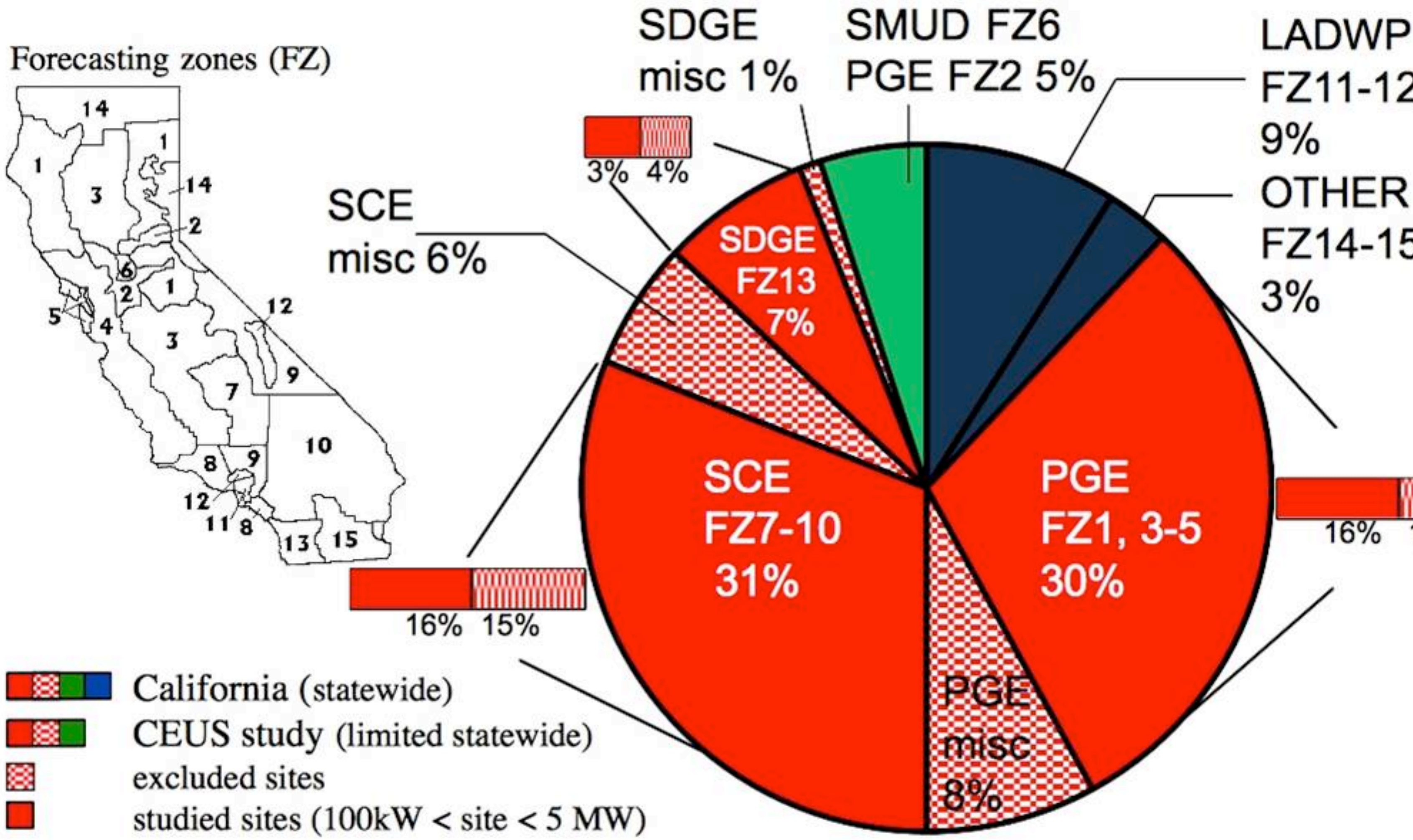
- PG&E A1 buildings with peak demand 200-500 kW
- dmd. chrg. > $10/kW/mo.
- connection payment 200 $/kWh/a
- stationary storage at 60 $/kWh investment cost
- energy exchange price 5 $/kWh
- net annual zero transfer

| | |
|---|---|
| Time of connection | 9:00 |
| Time of disconnection | 18:00 |
| SOC in [%] | 73% |
| SOC out [%] | NONE |

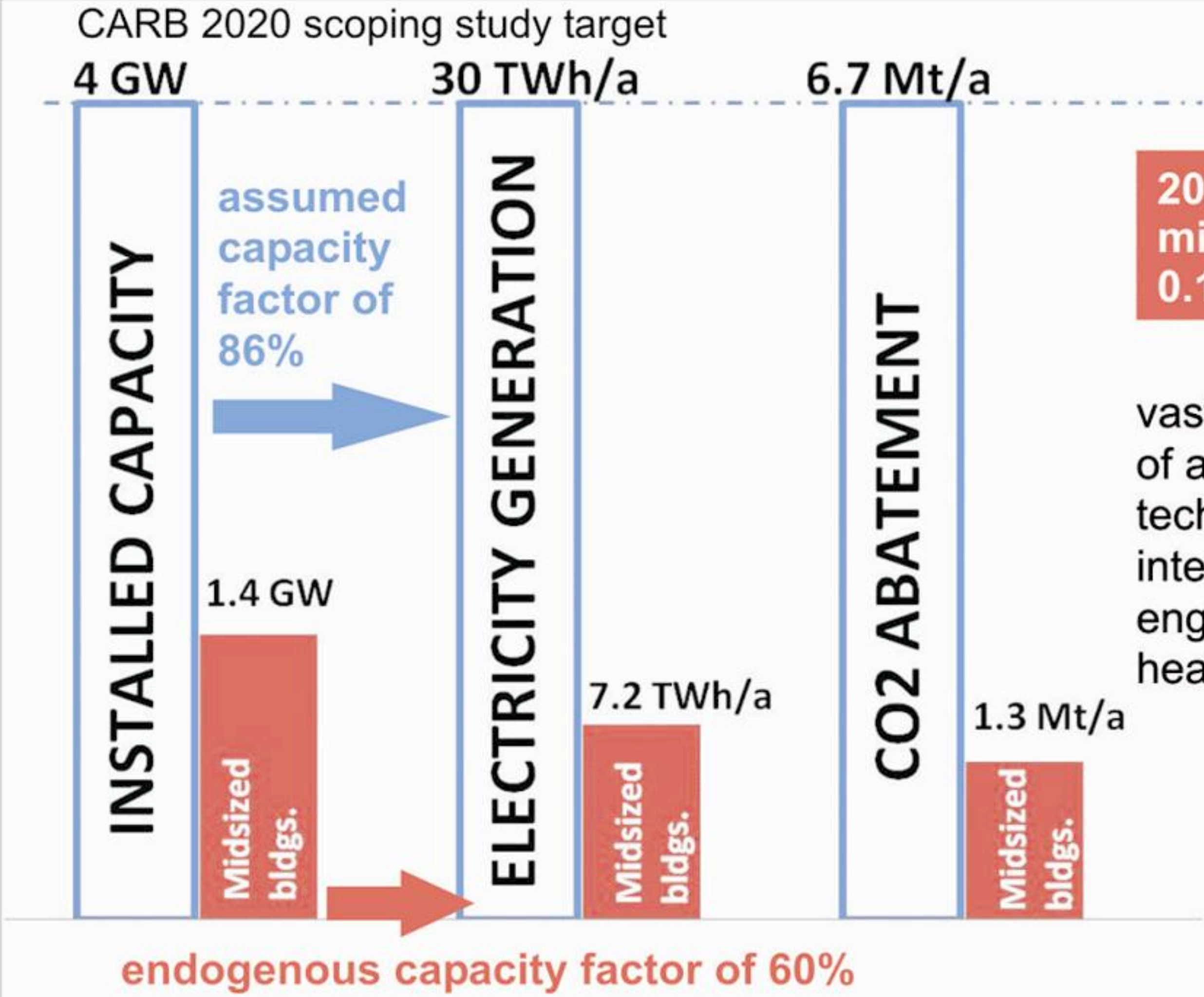
Installed capacity of 50 kWh mobile storage translates into about 5 PHEVs with 16 kWh name plate battery capacity each



# Sample ~35% of CA Com. Sector Demand



# Results Summary



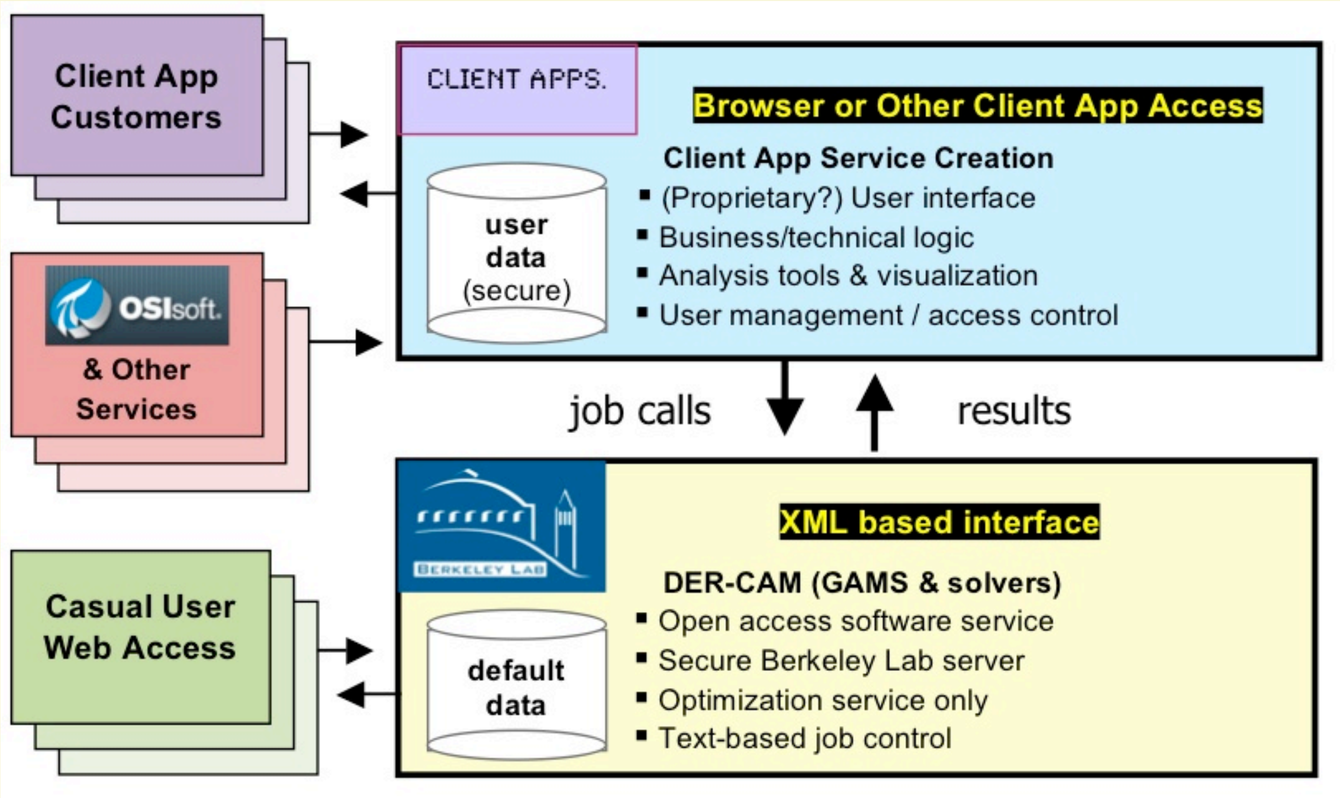

2020 cost savings midsized bldgs: 0.19B$/a

vast majority of adopted technologies are internal combustion engines with heat exchangers

# DER-CAM Commercialization

GAMS doesn't offer a good path to commercialization: academic, cryptic text interface, expensive, …

Software as a Service model is one solution.



# What next?

## ACTIVE

- battery evaluation web site for large CA C&I customers
- adding electric vehicle interactions (V2G & V2M)
- dynamic control (Energy Manager)
- residential and small commercial DC systems

## WISH LIST

- energy efficiency
- commercialization as SaaS
- more on PQR (DC systems)
- more on EV's (joint optimization)
- applied dynamic control
- Uncertainty
- links to building energy simulation

# Microgrids

# What is a Microgrid?

A ***controlled*** grouping of energy (including electricity) sources and sinks that is connected to the macrogrid but can function independently of it.

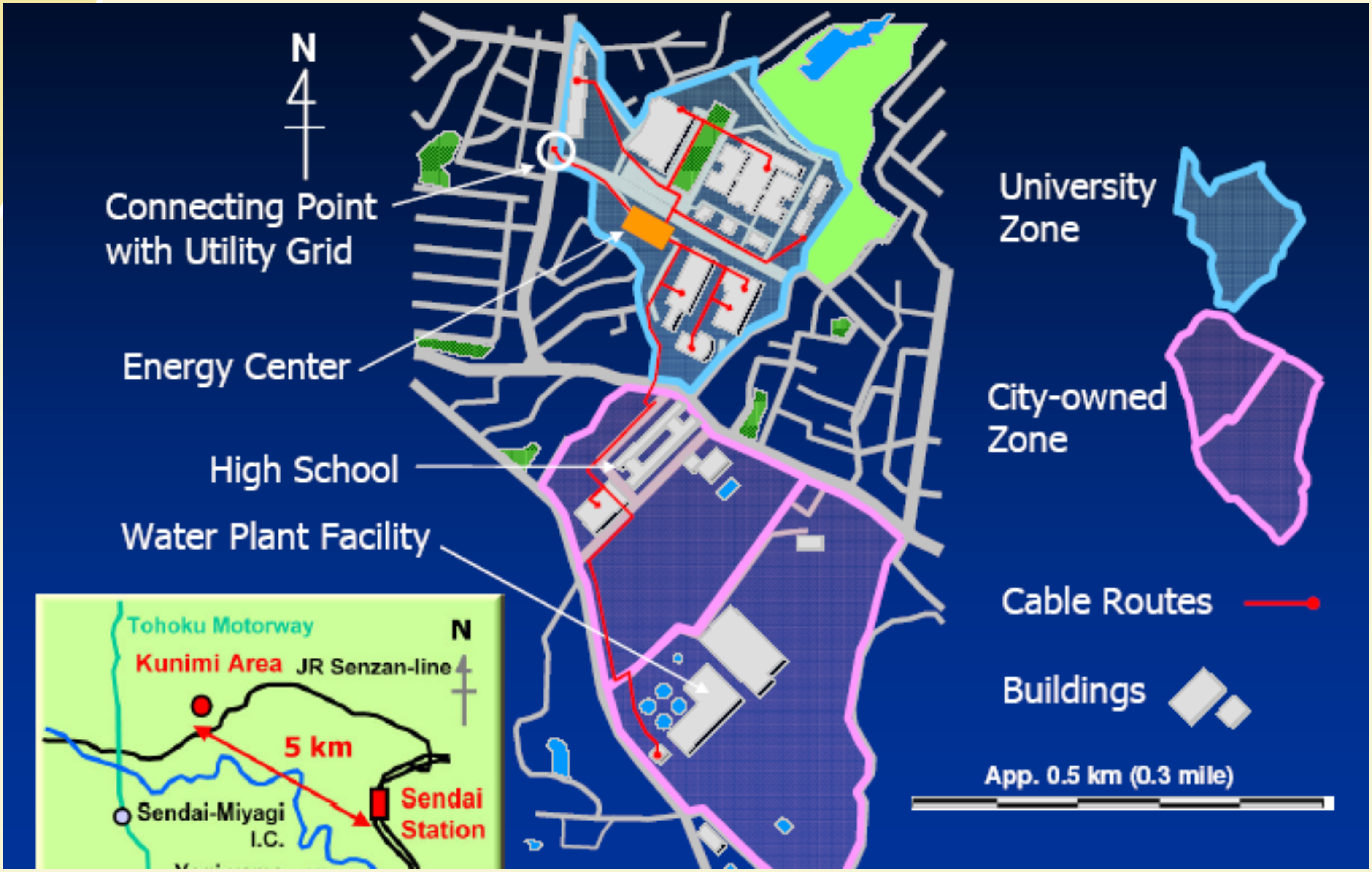
**main benefits to developers of microgrids:**

- **pushing efficiency limits by heat recovery (CHP)**
- **providing heterogeneous power quality and reliability (PQR)**
- **creating a more favorable environment for efficiency and small-scale renewables and/or protecting the grid from them**

**other societal benefits include:**

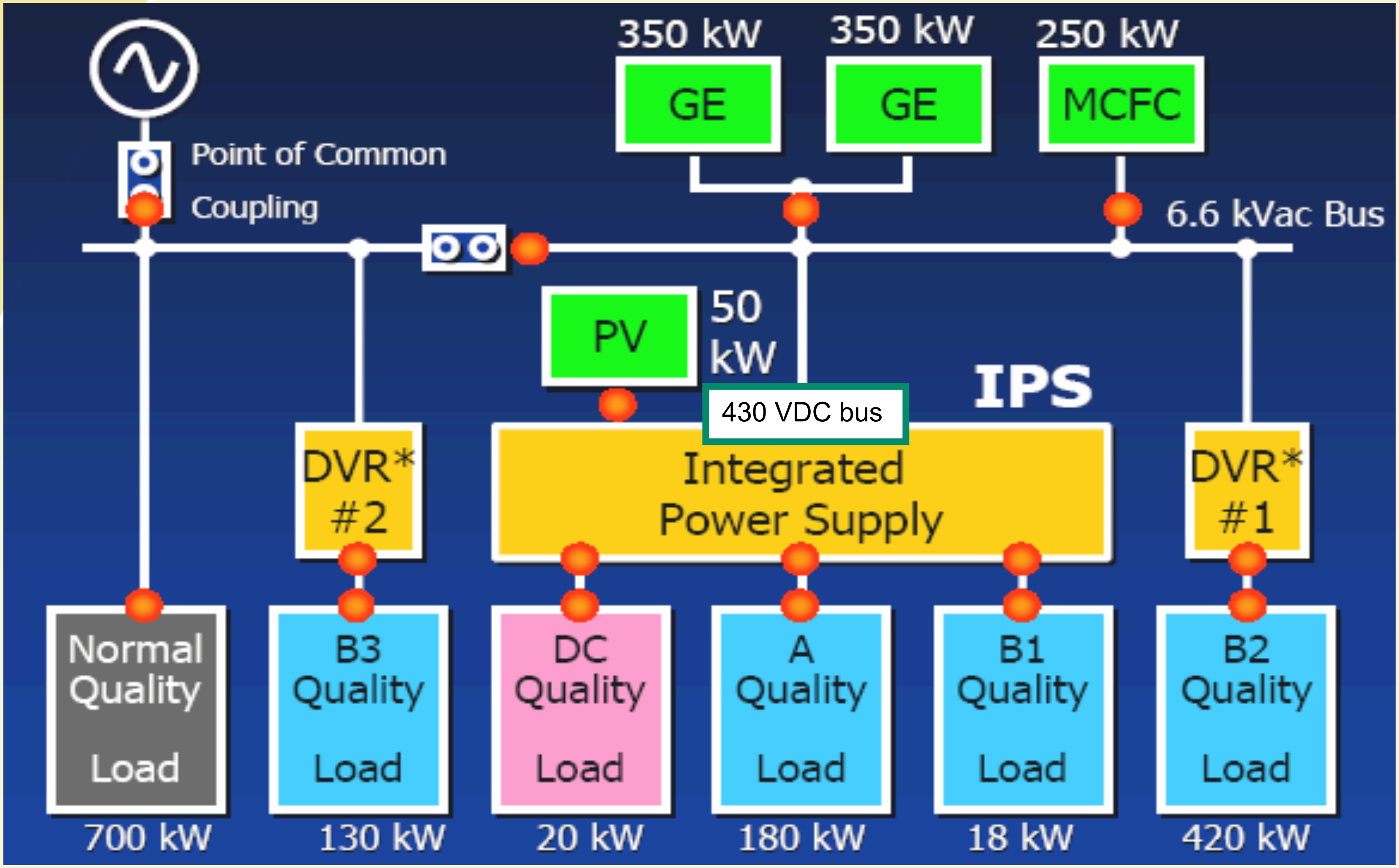
- **avoiding macrogrid investments**
- **hardening of supply**
- **curbing generator market power, etc.**
- **load leveling**

# Sendai Project Plan

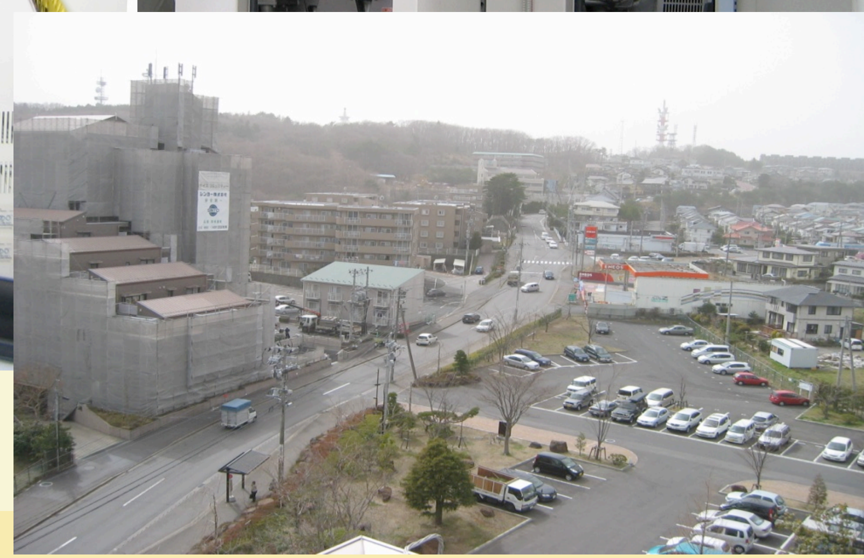


# Sakura at Sendai Microgrid

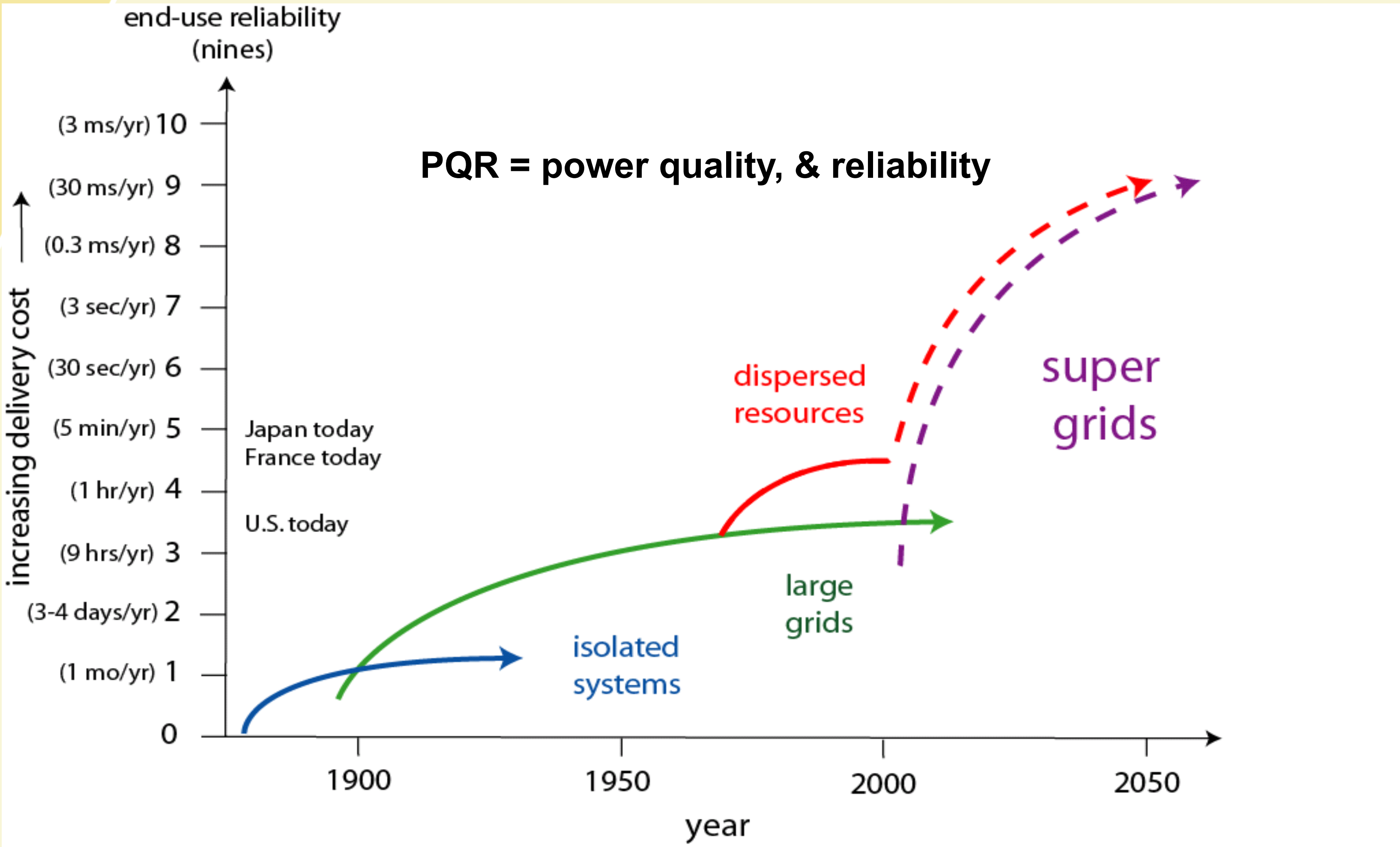
# Sendai Project Schematic



# Sendai Project Pictures

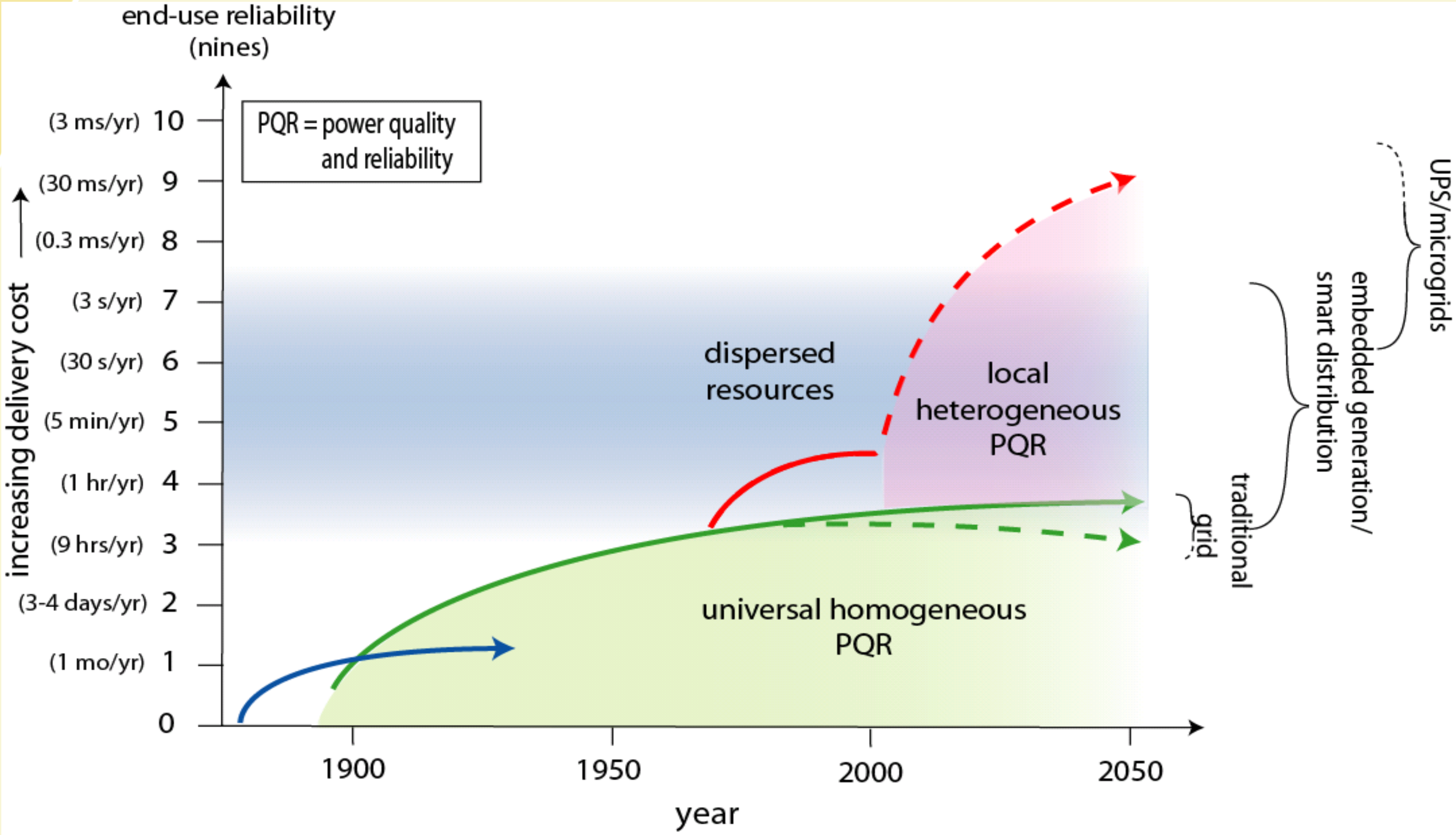



# Supergrid Vision

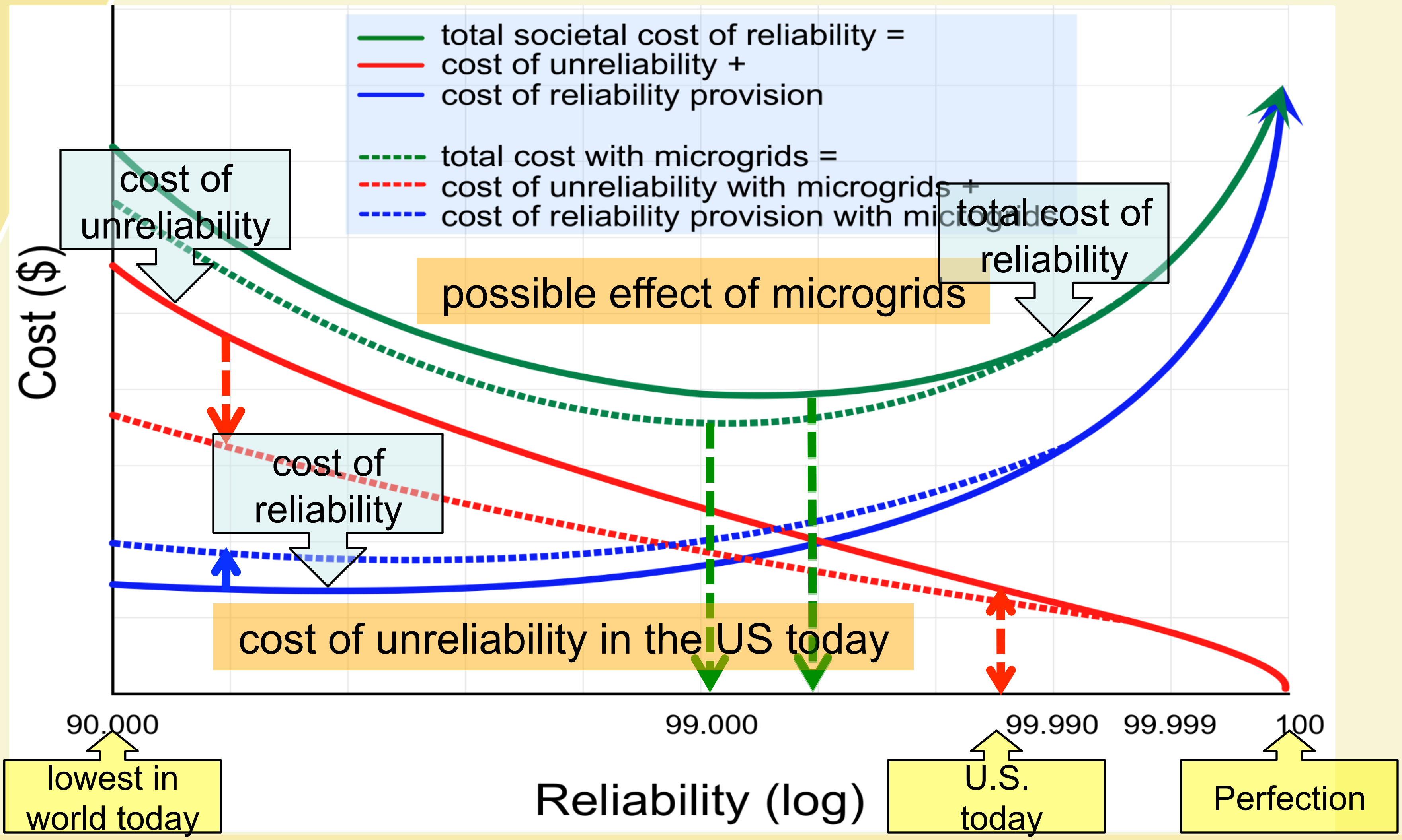


# Dispersed Vision

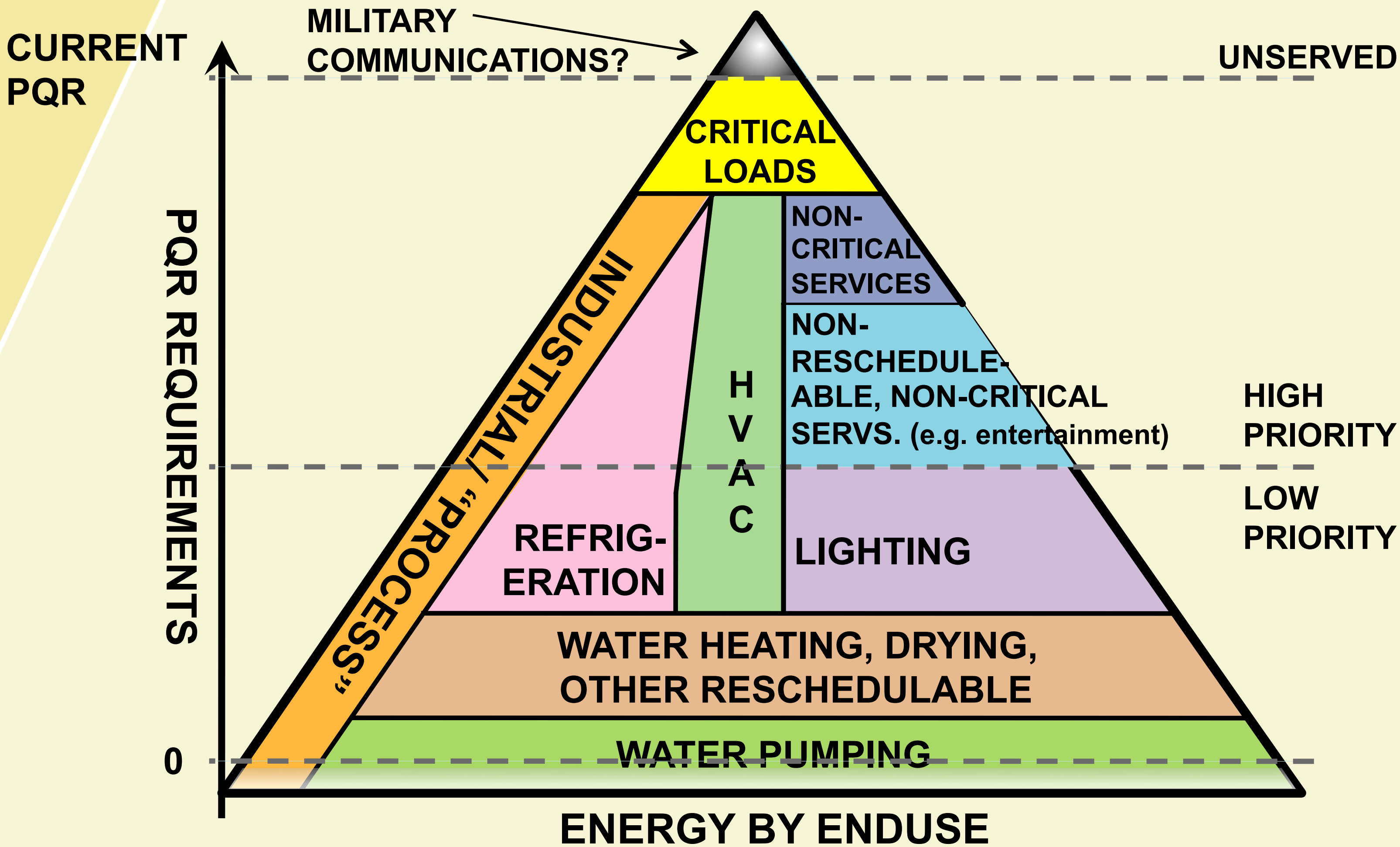
**(distributed control & heterogeneous service )**



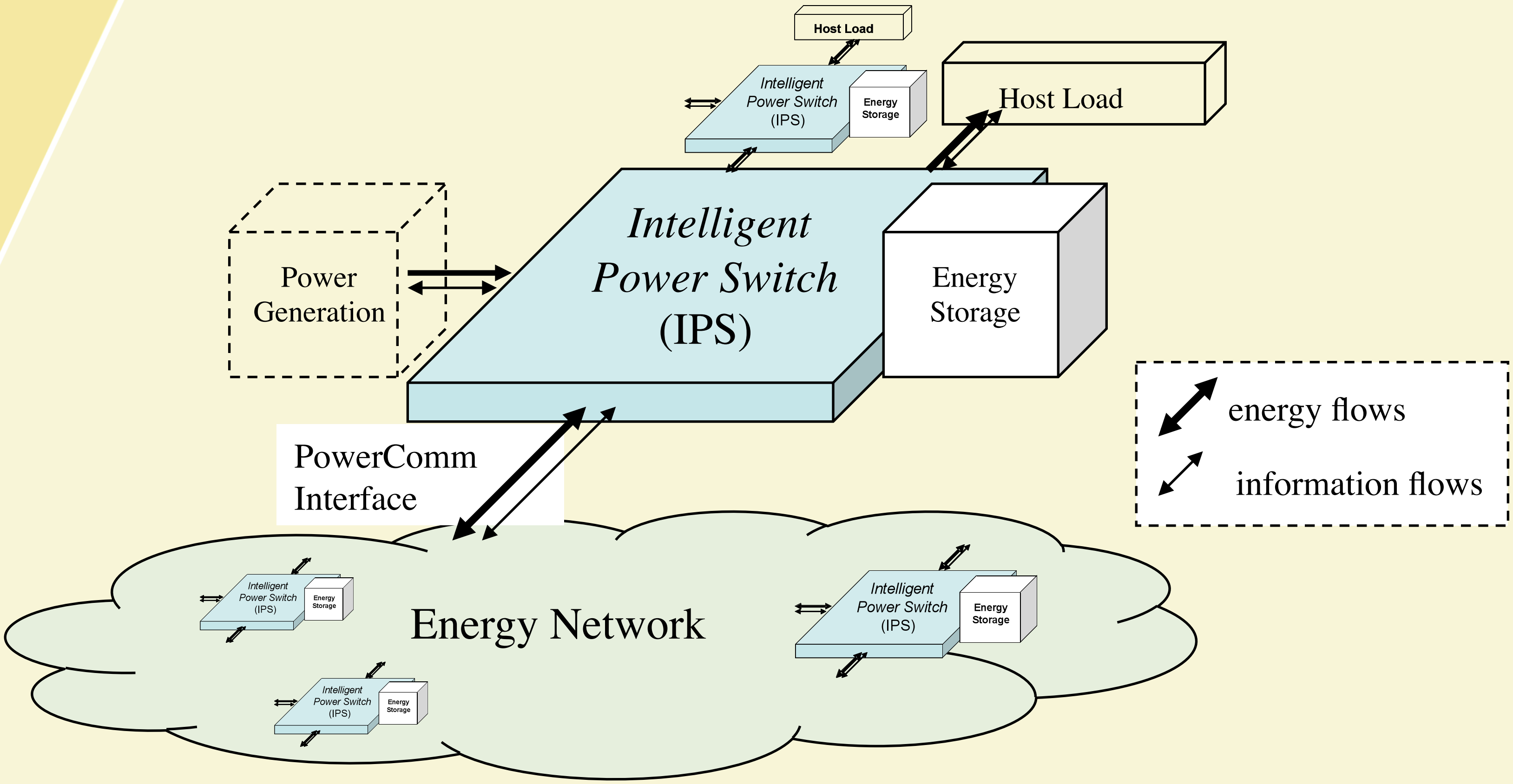
# Choosing Universal Service Quality



# Loads Disaggregated by PQR Requirements



# Intelligent Power Switch



# DER-CAM
# Modeling Issues

# DER-CAM Description

- Mixed Integer Linear Program (MILP), written in the General Algebraic Modeling System (GAMS®)
- minimizes the annual energy services bill (or carbon emissions, or multiple objectives, or …) of providing services on a microgrid level (typically buildings with 250-2000 kW peak)
- produces technology neutral pure optimal results with highly variable run times
- used for more than 5 years by Berkeley Lab and under license by researchers in the US, Germany, Spain, Belgium, Japan, and Australia
- potentially commercialized (software as a service model)

# Cost Objective Function

$$
\begin{aligned}
Cost = & \sum_{m\in M} \mathrm{ContractDemandCharge} \cdot \max_{m\in M, t\in T, h\in H} \left\{ \mathrm{Load}_{'e',m,t,h} + \mathrm{Load}_{'c',m,t,h} \right\} + \sum_{m\in M} \mathrm{MonthlyFeeElectric} \\
& + \sum_{m\in M}\sum_{i\in I} \left( DERInvestment_i \cdot \mathrm{Maxp}_i + Capacity_{'pv'} \right) \mathrm{StandbyCharge} + \sum_{m\in M}\sum_{p\in P}\sum_{t\in T}\sum_{h\in p} ElectricityPurchase_{m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{ElectricityRate}_{m,p} \\
& + \sum_{m\in M}\sum_{d\in D} \mathrm{MonthlyDemandRates}_{m,d} \cdot \max_{t\in T, h\in d} \left\{ ElectricityPurchase_{m,t,h} \right\} + \sum_{m\in M}\sum_{t\in T}\sum_{d\in D} \mathrm{DailyDemandRates}_{m,d} \cdot \mathrm{N}_{m,t} \cdot \max_{h\in d} \left\{ ElectricityPurchase_{m,t,h} \right\} \\
& + \sum_{m\in M}\sum_{t\in T}\sum_{h\in H} ElectricityPurchase_{m,t,h} \cdot \mathrm{MktCRate} \cdot \mathrm{N}_{m,t} \cdot \mathrm{CTax} - \sum_{i\in I}\sum_{m\in M}\sum_{t\in T}\sum_{h\in H} GenX_{i,m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{PX}_{m,t,h} \\
& - SwitchPurchase \cdot \mathrm{StaticSwitchParameterValue} \cdot \mathrm{SwitchSize} - \sum_{m\in M}\sum_{t\in T}\sum_{h\in H} ElectricityPVExport_{m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{PX}_{m,t,h} \\
& + \sum_{m\in M}\sum_{t\in T}\sum_{h\in H}\sum_{i\in I_{NG}} \left( GenL_{i,m,t,h} + GenX_{i,m,t,h} \right) \cdot \frac{1}{\mathrm{E}_i} \cdot \mathrm{N}_{m,t} \cdot \left( \begin{aligned} & \mathrm{NGBasicPrice}_m \\ & + \mathrm{NGCarbonEmissionsRate} \cdot \mathrm{CTax} \end{aligned} \right) \\
& + \sum_{m\in M}\sum_{t\in T}\sum_{h\in H} NGforHeat_{m,t,h} \cdot \mathrm{N}_{m,t} \cdot \left( \begin{aligned} & \mathrm{NGBasicPrice}_m \\ & + \mathrm{NGCarbonEmissionsRate} \cdot \mathrm{CTax} \end{aligned} \right) + \sum_{m\in M}\sum_{t\in T}\sum_{h\in H}\sum_{i\notin I_{NG}} \left( GenL_{i,m,t,h} + GenX_{i,m,t,h} \right) \cdot \frac{1}{\mathrm{E}_i} \cdot \mathrm{N}_{m,t} \cdot \mathrm{OtherFuelPrice}_i \\
& + \sum_{m\in M}\sum_{t\in T}\sum_{h\in H}\sum_{k\in K} NGforNGChill_{k,m,t,h} \cdot \mathrm{N}_{m,t} \cdot \left( \mathrm{NGforABS}_m + \mathrm{NGCarbonEmissionsRate} \cdot \mathrm{CTax} \right) \\
& + \sum_{m\in M} \left( \mathrm{MonthlyFeeNGBasic} + \mathrm{MonthlyFeeNGforDG} + \mathrm{MonthlyFeeNGforABS} \right) + \sum_{i\in I} DERInvestment_i \cdot \mathrm{Maxp}_i \cdot \mathrm{CapCost}_i \cdot \mathrm{Annuity}_i \\
& + \sum_{k\in K} NGChillPurchaseQuantity_k \cdot \mathrm{Maxp}_k \cdot \mathrm{CapCost}_k \cdot \mathrm{Annuity}_k + \sum_{\ell\in L} \left( Purchase_\ell \cdot \mathrm{FixedCost}_\ell + Capacity_\ell \cdot \mathrm{VariableCost}_\ell \right) \cdot \mathrm{Annuity}_\ell \\
& + SwitchPurchase \cdot \left( \mathrm{SwitchSize} \cdot \mathrm{CostM} + \mathrm{CostB} \right) \cdot \mathrm{AnnuitySwitch} + \sum_{m\in M}\sum_{i\in I} DERInvestment_i \cdot \mathrm{Maxp}_i \cdot \frac{\mathrm{OMFix}_i}{12} \\
& + \sum_{m\in M}\sum_{\ell\in L} Capacity_\ell \cdot \mathrm{FixedMaintenance}_\ell + \sum_{m\in M}\sum_{k\in K} NGChillPurchaseQuantity_k \cdot \mathrm{Maxp}_k \cdot \frac{\mathrm{OMFix}_k}{12} \\
& + \sum_{m\in M} \left( \sum_{k\in K}\sum_{t\in T}\sum_{h\in H} NGChillAmount_{k,m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{OMVar}_k \right) + \sum_{m\in M} \left( \sum_{i\in I}\sum_{t\in T}\sum_{h\in H} \left( GenL_{i,m,t,h} + GenX_{i,m,t,h} \right) \cdot \mathrm{N}_{m,t} \cdot \mathrm{OMVar}_i \right) \\
& + \sum_{d\in D}\sum_{m\in M}\sum_{t\in T}\sum_{h\in H} DemandResponse_{d,m,t,h} \cdot \mathrm{N}_{m,t} \cdot \mathrm{DemandResponseVC}_d
\end{aligned}
$$

# Available Equipment

## discrete

| | CM-100 | fuel cell |
|---|---|---|
| capacity (kW) | 100 | 200 |
| sprint capacity | 125 | |
| installed costs ($/kW) | 2400 | 5005 |
| with heat recovery ($/kW) | 3000 | 5200 |
| variable maintenance ($/kWh) | 0.02 | 0.029 |
| efficiency (%, HHV) | 26 | 35 |
| lifetime (a) | 20 | 10 |

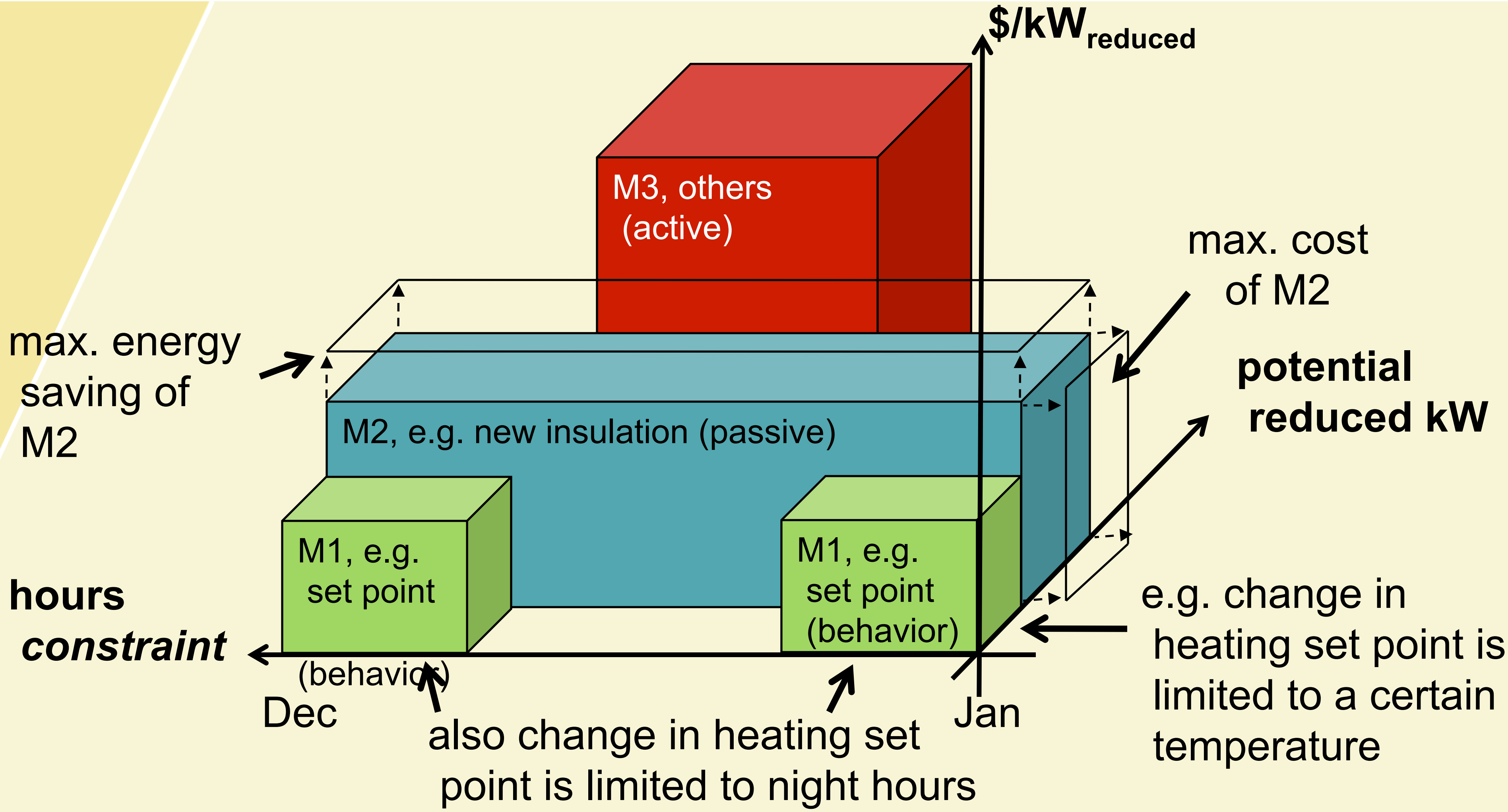
only integer installations

## continuous

fixed unavoidable costs

| | electrical storage (lead acid) | thermal storage | flow battery | absorption chiller | solar thermal | PV |
|---|---|---|---|---|---|---|
| intercept costs ($) | 295 | 10000 | 0 | 20000 | 1000 | 1000 |
| capacity ($/kW or $/kWh) | 193 | 100 | 2125/220 | 127 | 500 | 6675 |
| lifetime (a) | 5 | 17 | 10 | 15 | 15 | 20 |

# Dmd. Measure Potential



# Zero Net Energy Bldgs.

- ZNEB constraint: purchased energy = sold energy
- energy must be in common units (heat equivalent)
- footprint constraint: the possible space for PV and solar thermal adoption must be restricted
- multiple possible minimization objectives:
  - energy or energy bill
  - carbon emissions
  - combination or other
- consideration of demand response measures:
  - load shifting measures represented by storage
  - load reduction measures represented by abstract *low*, *mid*, and *high* measures

# PQR at 3 Example Bldgs.

| | Floor-space (000 $m^2$) | peak load (MW) | annual electricity (GWh) | annual NG (TJ) | Fs, base | Fs, peak |
|---|---|---|---|---|---|---|
| nursing home | 32 | 0.96 | 5.8 | 20 | 0.5 | 0.1 |
| school | 18 | 0.88 | 1.5 | 2.6 | 0.25 | 0 |
| data center | 0.6 | 1.8 | 11.4 | 0 | 1 | 1 |

# Detailed CM Results

| cases / chosen equipment | nursing home utility | nursing home opt invest | nursing home CM | school utility | school opt invest | school CM | data center utility | data center opt invest | data center CM |
|---|---|---|---|---|---|---|---|---|---|
| CM-100 + CHP (kW) | na | 300 | 300 | na | 0 | 0 | na | 0 | 1600 |
| switch size (kW) | | na | 260 | | na | 9.7 | | na | 1788 |
| abs. chiller (kW.e) | | 48 | 48 | | 139 | 136 | | 141 | 316 |
| solar therm (kW.t) | | 134 | 134 | | 65 | 65 | | 0 | 0 |
| elect. storage (kWh) | | 0 | 0 | | 0 | 47 | | 0 | 0 |
| therm. stor. (kWh) | | 0 | 0 | | 0 | 0 | | 0 | 0 |
| **results: costs, energy consumption, emissions, and savings** | | | | | | | | | |
| electricity (k$/a) | 758 | 429 | 429 | 264 | 246 | 242 | 1478 | 1459 | 871 |
| NG (k$/a) | 206 | 359 | 359 | 24 | 26 | 26 | 1.8 | 9.7 | 322 |
| on-site DG (k$/a) | na | 138 | 135 | na | 7.44 | 254 | na | 4.0 | 249 |
| Total cost (k$/a) | 964 | 926 | 924 | 288 | 280 | 280 | 1480 | 1473 | 1443 |
| electricity (GWh/a) | 5.8 | 3.2 | 3.2 | 1.5 | 1.5 | 1.5 | 11.42 | 11.4 | 8.44 |
| NG (GWh/a) | 5.7 | 10.0 | 10.0 | 0.7 | 0.8 | 0.8 | 0.0 | 0.23 | 9.14 |
| C emissions (t/a) | 1088 | 945 | 945 | 360 | 358 | 358 | 1599 | 1606 | 1634 |
| CM val. ($/kW*a) | na | na | <=25 | na | na | <=25 | na | na | <=125 |
| % cost savings (k$/a) | na | 3.9 | 4.1 | na | 2.87 | 2.83 | na | 0.47 | 2.50 |
| % C savings (tC/a) | na | 13.1 | 13.1 | na | 0.58 | 0.52 | na | -0.5 | -2.0 |

* no subsidies considered in optimum invest case

# Thank you!

http://www.youtube.com/watch?v=3XuCJBvq6Sk

http://der.lbl.gov